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UNITED STATES OF AMERICA

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Iceland is far ahead of the rest of the world in the use of geothermal energy for hot water and space heating, but they have run into severe difficulties in generating electricity from this source. The present report describes these difficulties and some of the people involved.

ENERGY FROM THE BOWELS OF THE EARTH—
VULCANISM AND ITS USES IN ICELAND

Most of Iceland is just south of the Arctic Circle, but the midnight sun may still be seen to the north in June because of atmospheric refraction. While some parts of the interior are glaciated, much of Iceland's coastal region has a moderately mild climate. It never gets hot in summertime, but on the other hand, the winters are not as cold as those in Chicago because of the moderating effect of the Irminger Current, a branch of the Gulf Stream which flows along the South Coast of the island. Nonetheless it is much colder than countries such as England, and a good deal of space heating is required.

At the present time 70% of all the houses in Iceland obtain their space heating from geothermal energy, and it is expected that in a few more years that fraction will be near 80% (now considered the ultimate limit). In this respect Iceland is far ahead of the rest of the world. Hot water also comes from geothermal energy, but as of now very little electric power has a geothermal source. Many other countries, including the United States, produce a good deal more electric power from geothermal energy than Iceland does. Whether this will continue to be true is not now clear. As is discussed below, a good deal of controversy surrounds the development of electrical power from geothermal sources in Iceland.

The formal exploitation of geothermal energy in Iceland began in 1928 when a well near Reykjavik, the capital, began producing 14 liters per second of 87°C water, which was piped a distance of 3 kilometers and used to heat a newly built swimming pool, a hospital, 2 schools, and 70 homes. In the words of Sveinbjörn Björnsson, professor of geophysics at the University of Iceland, and brother of Sigfus Björnsson, mentioned in the article OR in Iceland (*ESN* 34-10:486) as the operation was to commence, "it is said that there came a message from the Bishop that he wanted to come and bless the facilities to ensure that God would favor the undertaking. This kind offer was courteously turned down as some felt not sure whether the supplier of the heat underground could withstand a splash of holy water."

Ninety-eight percent of the houses in Reykjavik and its suburbs, constituting approximately half the population of the entire country, now obtain their heat and hot water from geothermal sources. The heating bills of these consumers average less than 1/4 of what they would be with oil furnaces—and without any subsidy. The hot water comes from distances up to 18 kilometers away, from some 40 wells 800-2000 meters deep, producing 1800 liters/second of water, at temperatures in excess of 100°C. Some of this water, after being used in the homes, is dischar into the ocean; the rest is pumped back to the wellheads where it is mixed with the incoming hot water to maintain a steady supply temperature

of 80°C. This hot water is not only used for heating, but also is passed directly into the hot-water pipes. The cold water from the taps in Reykjavik is untreated and is the most remarkably delicious of pure waters. The hot water from the same taps has come without treatment directly from the geothermal bore holes, and smells faintly of sulfur. In many other communities in Iceland the geothermal water has too great a solid content for direct use in this way, and therefore cold water is heated by the geothermal water to provide hot water for homes.

A few homes in Iceland are heated by unusual devices. For example, the Westman Islanders had most of their town destroyed by a volcanic eruption in 1973. The lava flow has now cooled on the outside but a great body of magma (fluid lava) remains trapped inside and is not expected to solidify for at least 10 years. The Westman Islanders have been carefully watering this lava to obtain hot water to heat their reconstructed houses.

Such volcanic eruptions are not uncommon in Iceland. There has been an average of one eruption every 5 years somewhere in the country, and a typical eruption consists of a long sequence of episodes which may involve numerous lava flows over several years. In Krafla, for example, discussed below, an eruption started with seismic activity in the middle of 1975, culminating in a major lava flow in December of that year, followed by two more lava flows in 1977, and by another in March, 1980. Whether that eruption is yet complete is unclear at this writing. That the Icelanders have learned to live with this situation is due in part to the fact that most of these eruptions are not so violent as those of our own Mt. St. Helens. In the latter, the magma contained a great deal of silica and was therefore highly viscous. This meant that pressure built up to a considerable extent before it was finally relieved by a violent episode.

The magmas in Iceland tend to be more basaltic and therefore less viscous, but there are exceptions. On the Island of Heimaey, a volcano which had been inactive for 5,000 years erupted violently and suddenly one night in 1973. Fortunately there had been a storm that day, and as a result the entire fishing fleet was in the harbor when the volcano erupted; this fleet was thus available to evacuate the entire population, and no life was lost. Later, however, many roofs collapsed from the weight of the ash on them, and a number of homes were destroyed by fires started by red-hot stones which hurtled through windows. There are numerous other tales of violent explosions.

Krafla had not erupted since 1724, and the eruption in 1975 was completely unanticipated. It represented a rather extraordinary and unfortunate coincidence. Electric power for all of Northern Iceland was being brought in from petroleum-burning power stations in the south hundreds of kilometers away. This was an undesirable arrangement because of the transmission line losses, and it became even more undesirable when the price of oil was raised drastically in 1973.

There had long been plans for a major hydroelectric development to supply the necessary electric power in Northern Iceland, but the proposed development had been surrounded by controversy on environmental grounds. In 1974 the environmentalists won, the hydroelectric plans were canceled, and the decision was made to build a plant to develop electric power from geothermal energy. A gamble was then taken, in which it was decided to have a crash development at Krafla without going through the usual preliminary stages. For example, one normally drills the wells and tests the steam elaborately before ordering turbines which are adapted to the particular type of steam found in the region. In this instance, steam had been used for some time in a nearby region as a source of process heat in a plant manufacturing diatomaceous earth, and the developers decided to gamble that the same type of steam would be found at Krafla. They therefore proceeded to order two 37.5 MW turbines and generators from the Mitsubishi Company in Japan to utilize that type of steam. A few days after those contracts were signed, the above-mentioned seismic activity started. At that point it became clear that Krafla was not an ideal site for such a power plant; whenever such a disturbance develops, significant changes take place underground, and these may affect the production of steam from wells already drilled. However, so much money had already been invested that the development proceeded.

When the wells were sunk, another misfortune developed. The structure and the nature of the hot water that was encountered were unique not only for Iceland but for the entire world. The turbines that had been purchased were optimized for water at about 260°C. At about 800 meters the drillers found water at 200°C, not hot enough to be useful; they then ran into a layer of rock, and below this, at depths of 1500-2000 meters, they struck water at 300-350°C—too hot for appropriate and efficient use. Furthermore it was a two-phase system, that is, a mixture of steam and water, which meant that the amount of hot fluid coming up the pipes was less by a factor of 10 than it might have been with a single phase at the source. In addition, a special plant was required to separate the steam from the hot water before bringing the steam into the turbines. On top of that, some of the wells provided water which had a great deal of noncondensable gas (mostly carbon dioxide) which required continuous bleeding from the turbine exhaust at considerable expense. Finally, this water also had a great deal of solids, which tended to deposit and clog the pipes. In at least one case this caused the pressure to build up drastically; thereafter things got out of hand, and a few hours later the entire well blew up, leaving a crater looking very much like that of a small extinct volcano.

Now, five years later, the situation seems well under control from a scientific and engineering viewpoint, but there are severe difficulties from a political point of view. With some 50 million dollars invested thus far on the power plant, the wells, and the transmission line which carries the electricity away from Krafla, a total of about 7 MW net is being produced after subtracting the power used at the plant itself.

One of the turbine generator sets has never been unpacked, and the other is operating well below capacity. It seems likely from a technical viewpoint that the eruption is nearly at an end and the region is becoming quiet, and if a few more wells were built, enough steam could be produced to have the plant operating at 70 MW, which was its design level. However, because of the difficulties that have occurred, the developers are having trouble obtaining the few million dollars required to build these extra wells and complete the enterprise.

There is no possibility that the source of heat will ever be over-exploited, but it is possible that the sources of water may be. That is, the geothermal water comes from ground water which has percolated down to great depths where it is heated by the underground magma. Special efforts may have to be made to return the geothermal water to the ground so that it will continue to be available. At this time there is no sign that such crises are imminent in Iceland. In El Salvador (Central America), it was found necessary to drill special holes into which the waste water from the geothermal power plants could be pumped, partly to ensure that there would be adequate underground water, and partly to eliminate a possible source of chemical and thermal pollution.

I am informed that the American astronauts did some of their training in Iceland because the landscape closely resembles that of the moon. I can believe it, because the area around Krafla, like many other parts of Iceland, is incredibly bleak. Steam can be seen issuing from the ground, the smell of sulfur is everywhere, and there is no sign of any plant life except for an occasional tuft of grass (remarkably, there are sheep in the area who live off these occasional tufts). I was shown around the area by Gunnar Gunnarsson, a plant engineer in charge locally, and by Trausti Hauksson and Halldor Armannsson, both of whom work at the National Energy Authority in Reykjavik but who spend a great deal of time around Krafla. (To get to Krafla one flies to Akureyri, the capital of Northern Iceland, and then drives 107 kilometers over dirt roads to the small town of Reykjahlið, which is only a few kilometers from Krafla.) Gunnarsson and Hauksson are electrical engineers trained in Denmark and Sweden respectively, and Armannsson is a chemist who took a doctorate at Southampton, and who as a result speaks with a charming British accent with no trace of Icelandic. Gunnarsson is responsible for keeping the plant going, and is confident that he can maintain the 70 MW production rate 24 hours a day, 7 days a week, if he is given the necessary steam. Hauksson and Armannsson are optimistic about the nature of the steam that can be produced if the wells are sunk where they feel the steam will be of the right sort.

The man with the real responsibility for making these decisions is Einar Elíasson, the manager of the Rarik-Krafla division (Rarik is an acronym for the Icelandic words which designate the State Electric Power Works of Iceland). The Krafla operation was originally run by a number of diverse groups, and Elíasson assured me that it was indeed "a camel" (which, according to the old aphorism, is a horse built by a

committee). Elíasson who speaks with a strong Scottish burr, took his doctorate in mechanical engineering in Glasgow and taught at Strathclyde University for 10 years before returning to Iceland. He is the one who makes the decisions and balances costs against other factors. For example, the geologists and chemists may indicate the most likely place for a well to get desirable water, but if that place is on a mountain top he has to consider that it may adversely affect the aesthetics for many miles around, whereas a well a short distance away could be virtually invisible. Furthermore, one knows where the top of a well is but one doesn't necessarily know where the bottom is going to be; that is, it is difficult to make the well exactly vertical. Elíasson also has to balance questions of reliability and safety. At the diatomaceous earth plant I saw a steam well where, during one of the recent volcanic episodes, magma actually came up the pipe which was supposed to carry steam. It goes without saying that this well is no longer in use for producing steam; I cite it here to illustrate the obvious fact that there are always dangers lurking in an area of active vulcanism.

Elíasson is convinced that within 5 years at the most, 60-70 MW will be coming out of the transmission lines from Krafla, and he is already making plans to exploit geothermal energy for electric power production elsewhere. This energy or some other nondepletable source of electric power is essential for Iceland which, like so many other countries, has no native fossil fuel and has great difficulty paying for imported petroleum. There is scarcely any alternative to petroleum for transportation, but for all other purposes Iceland hopes to use geothermal or hydroelectric power exclusively.

Prospecting for geothermal water is similar in some ways to prospecting for petroleum. There is currently a great deal of geological and geophysical research in this connection. Much of this research in Iceland is concentrated in the Science Institute of the University of Iceland where I talked to Sveinbjörn Björnsson, mentioned above. He did his graduate work in geophysics at Aachen, Germany. Björnsson has set up 35 seismic stations all over Iceland to monitor all the volcanos that might erupt as well as the seismic zones where earthquakes are likely to occur. Some of the support for this effort comes from NATO. This network has produced a great deal of data which is useful in developing theory which will facilitate the prediction of earthquakes. He has also been engaged in the study of historical data. From the time Iceland was settled in 874 AD, excellent records have been kept, and some of these records contain a great deal of historical information about the seismic activity. Several earthquakes in recent times have measured 7 or more on the Richter scale. In the last 100 years, there has been a great deal of urbanization, with significant possibility of considerable damage if an earthquake should occur near one of the cities.

Björnsson has also been doing research on resistivity methods of geothermal exploration. By putting two electrodes into the earth and measuring the resistance between them, one can get a great deal of

information, primarily on the amount of water in the ground, but also on the temperature of the water and a number of other factors. If the probes are sufficiently far apart, one can get information at depths to one or two km. The geophysicist wishes not only to find hot water, but also to delineate precisely the boundaries of the region where that hot water is located. Such geophysical methods as resistivity measurements are enormously less expensive than drilling exploratory wells. Finally, Björnsson runs the University of Iceland geothermal energy course for the United Nations University. This is a university without a campus, headquartered in Tokyo, which pays travel expenses and stipends for students, mostly from underdeveloped countries, at many universities all over the world. The host country pays for the teachers and the facilities. Students in this course come from such places as the Phillipines, El Salvador, Honduras, and the People's Republic of China, where exploitation of geothermal energy is just getting under way.

Björnsson told me that using geothermal energy for electric power is much less efficient than using it for heating and he therefore predicted that, with the possible exception of some cogeneration plants, there would not be further development of geothermal electric energy in Iceland Apparently other people disagree with this opinion.

Geothermal research in Iceland is largely coordinated by the National Energy Authority. I talked with Gudmundur Pálmason, director of the geothermal division of that authority, and with Valgardur Stefánsson, deputy director and chief of the geothermal logging group. Pálmason has master's degrees from the University of Stockholm and Purdue University, Lafayette, IN, and also a DSc from the University of Iceland (while this university gives no graduate instruction, one may present and defend a thesis, which Pálmason has done).

The geothermal division has some 50 people, of whom 30-35 are professionals. The bulk of these people are involved in hot-water and heating projects, and in developing better methods for prospecting and the like. In addition to the resistivity mapping mentioned above, they are doing research on "self-potential" prospecting. The circulation of the thermal waters may develop potential differences amounting to a large fraction of a volt at points several kilometers apart. Thus far there has been little success in interpreting the measured potentials, but the research is proceeding with optimism.

The geothermal division has also made gravity maps of most of Iceland. There are major gravitational changes; the lowest gravity is at the center of the island while higher gravities are found around the coast, but there are also local anomalies representing density changes which give insights into underground formations. Finally, of course, there are also seismic studies.

Most of the geothermal activity in Iceland is associated with active vulcanism and this is concentrated in a zone along the ridges of the great

rift system which runs from Reykjavik, in the southwest corner, up to the Krafla region in the northcentral to northeastern portions of the country. All of the high-temperature water (greater than 150°C) is associated with these active zones. The lower-temperature water which can be used for heating (and which in fact is even better for heating because it contains less solids and undesirable gases) may be found outside these zones.

Stefánsson has a "fil.dr." from a Swedish university. When I asked him whether this was equivalent to an American PhD he replied "At least", his emphasis implying that it was a considerably higher degree. His logging group has developed methods of making measurements in bore holes, similar to what Schlumberger does for the petroleum industry, but Stefánsson's people have developed all this themselves, and they work with their own instrumentation. They measure, for example, temperature, pressure, temperature gradient, resistivity, gamma rays, gamma scattering, neutron scattering, and sonic velocity in the walls of the wells as the drilling procedes. All of this information tells a great deal about what is happening and supplements the cuttings which are brought to the surface. (In petroleum wells, the drillers normally bring cores up from the well to determine just what kind of rocks one is drilling through; however, this is too expensive for the geothermal development in which normally, rock dust which has a good deal less information is brought up.)

While petroleum drilling is usually done in sedimentary rocks, all the rock in Iceland is igneous, which makes for a great deal of difference in the interpretation and a whole new science of interpretation had to be developed. One new technique involves making resistivity measurements over vertical distances of 16 to 64 inches within the well. These measurements determine whether the rock is fractured or porous; most reservoir engineering is based on water traveling in porous media, but most geothermal reservoirs are dominated by fractured media. "To utilize a source, one must understand its behavior", Stefánsson told me.

To sum up, the exploitation of geothermal energy as a source of heat and hot water, not only for homes but also for industrial process heat, has proceeded extremely well in Iceland. The development of electric power from these sources has run into a string of bad luck, but it is in the hands of exceedingly competent people, and the future seems rosy.